ISSN 1392-3730 / eISSN 1822-3605

VILNIUS TECH
Vilnius Gediminas Technical University

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2026
Volume 32
Issue 6
Pages 785–799
https://doi.org/10.3846/jcem.2025.25511

BLOCKCHAIN FOR FIRE-RISK REDUCTION IN LONG-SCALE TUNNEL CONSTRUCTION

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Article History:
- received 27 May 2024
- accepted 6 August 2025

Abstract. Tunnel construction fire risk reduction is an integral component for tunnel construction safety. Recent fire cases during tunnel construction illustrate how existing management and prevention measures may fail in a fundamental and critical guarantee in the accuracy and authenticity of on-site information, thereby limiting the effectiveness of dynamic risk assessment management. To address this issue of information assurance, a fire risk reduction framework that integrates the Fault Tree analysis method with blockchain technology has been proposed. This framework develops some smart contracts and leverages digital signature to maintain data authenticity and ensure data immutability, contributing toward tunnel fire risk reduction by revealing responsible parties and maintaining information-source integrity. Based on this framework, a tunnel fire risk reduction platform using blockchain technology has been developed and applied in a practical engineering case study. The results indicate that this platform promotes open sharing of risk information, facilitates accident liability tracing, and supports dynamic risk assessment, ultimately improving the efficiency of fire risk reduction in tunnel construction.

Keywords: tunnel construction, fire risk, blockchain, responsibility tracing, risk reduction.

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1. Introduction

The current scale of tunnel construction in China is enormous, as shown in Figure 1. However, due to complex procedures, poor processes, and long construction duration, safety accidents frequently occur during tunnel construction. Fire safety management, especially in construction safety management, is a crucial aspect. Compared to typical surface building fires, tunnel construction projects, as one-dimensional linear underground structures, face greater firefighting challenges. These challenges include the concentration of personnel, equipment, and materials, numerous temporary electrical circuits at distant or advanced endpoints, long evacuation routes, limited rescue areas, and restricted access for rescue efforts (Zhao & Fang, 2007; Wang et al., 2011).

Plenty of data are produced and accumulated during the process of tunnel construction, while the multi-entity mode could make the information exchange and negotiation between entities and departments relatively ambiguous and vague. Data generated without a pre-planned systematic structure could lead to redundant and usually useless information (Xu et al., 2019; Yang, 2019; Yang et al., 2021). In order to meet the high-quality requirements and high-level standards, many entities have started to introduce information technology and deploy it into standardized management. Traditional management methods usu-

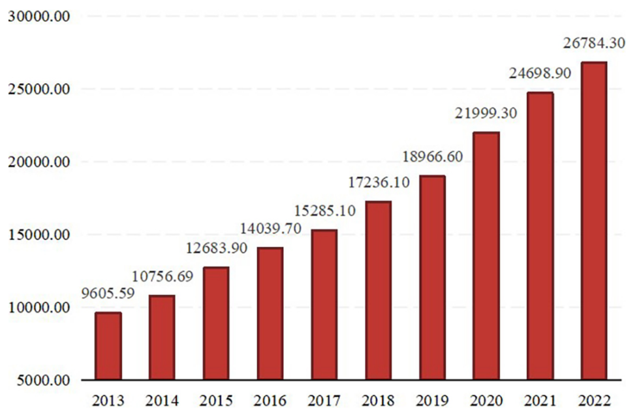

Figure 1. Total length of tunnels in China (km), 2013–2022

ally lack of coordination, and in turn may lead to poor information flow and low levels in utilization of data. Meanwhile, centralized systems require relying on the absolute trust of specific authorities with challenges related to transparency, equivalence, fairness and verifiability. Once data fraud or tampering occurs, the centralized system losses trust, making responsibility tracing more difficult after accidents happened. Therefore, two main problems are needed to address: (1) How can timely on-site fire risk inspections be ensured? (2) How can accurate, transparent, and traceable circulation of fire risk information among various responsible units be guaranteed?

The rapid development of blockchain technology provides an opportunity to address these issues. Blockchain technology is a new application pattern combining distributed data storage, peer-to-peer transmission, consensus mechanisms, and encryption algorithms (Nakamoto, 2009; Yuan & Wang, 2016). Due to its immutability and transparency, blockchain technology has huge potential for anti-tampering and traceability in the field of information management, and initially gained wide application in the financial field (Cryptocurrency Monitoring Website, 2015; World Economic Forum, 2016). Subsequently, scholars in the construction field attempted to apply blockchain technology to engineering construction and affirmed its prospects (Zhang et al., 2023; Zhu et al., 2022). Based on the transparency and anti-tampering characteristics of blockchain technology, it has found successful applications in monitoring data transmission during construction (Liu et al., 2021; Sheng et al., 2021; Zhong et al., 2022; Wu et al., 2022a, 2022b; Wang et al., 2022). On the premise of data authenticity, many scholars have proposed integrating blockchain technology with other technologies, expanding its application in the construction field (Wu et al., 2021; Pan et al., 2022).

In addition to information sharing and tracing, responsibility tracing is also an important part of risk reduction. Many scholars have integrated key business processes in engineering management into blockchain technology, enhancing the accountability of key information. A blockchain-integration process model has been proposed to simulate two potential conflict scenarios during construction and post-construction (Pradeep et al., 2021). Another example is the development of a construction supply chain system framework based on blockchain; the results indicate that accurate data can be retrieved for each request, and the corresponding reputation scores are successfully recorded (Lu et al., 2021). Researchers have also developed an innovative Two-Layer Adaptive Blockchain Supervision (TABS) model, which can prevent tampering with operation records and compel participants to disclose operation records without revealing privacy (Dinh et al., 2017). These scholars have explored different applications of blockchain technology in engineering construction from various perspectives. Considering that construction risk reduction is also a crucial part of construction management, exploring how to implement blockchain technology in construction risk reduction is an important goal of this study.

In summary, this study focuses on the information transmission and responsibility system for tunnel construction in order to realize refined management and supervision. It utilizes fault tree analysis data on factors contributing to fire accidents and outlines the fire risk information flow throughout the tunnel construction process. Additionally, it clarifies the responsibilities of each department and discloses fire safety risk information. Furthermore, this study also develops a prototype system based on WuTong-Chain to achieve risk visualization. This solution addresses the complexities of information flow and also increases the reliability of risk assessment results in large-scale tunnel projects, facilitating the implementation of targeted corrective measures on-site.

2. Literature review

2.1. Fire-related pain points of the current tunnel construction

Fire accidents are one of the most common incidents during tunnel construction, and the fire risk level is usually related to tunnel length (Yan et al., 2005). Generally, long tunnels are considered to be those with a total length of 3,000 to 10,000 meters, although the definitions of "long" and "short" tunnels vary depending on the firefighting perspective. A short tunnel is considered as one "where emergency operations would not be affected even in the event of a major fire". Long tunnel fire risks may exhibit the following characteristics (as shown in Figure 2): (1) the occurrence of fires is random in terms of time, location, type, and development; (2) exits or obvious escape routes may be out of sight for survivors; (3) there may be a significant amount of flammable and explosive materials around survivors during the initial stages of the fire; (4) firefighting forces typically enter the tunnel when the fire is already at its peak and out of control; (5) the nearest firefighting control point may exceed the maximum effective penetration distance of breathing apparatus (Liao et al., 2010; Li & Ingason, 2018).

The sources of fire risks on tunnel construction sites can generally be classified into two categories. The first category refers to energy or hazardous substances within the system that could accidentally be released and cause fires. This includes combustibles, ignition sources, and combustion-supporting materials (mainly oxygen content in the air). The second category refers to unsafe factors leading to the failure or destruction of measures that limit or constrain the release of fire energy. This includes issues related to humans, machines, environments, and management, such as unsafe behaviors, unsafe machinery states, adverse construction environments, and management deficiencies.

There are four main stages in safety management: risk identification, risk estimation, risk evaluation, and risk control decision-making. Risk decision-making can be divided into four categories: risk mitigation, risk reduction, risk transfer, and risk retention. Risk reduction involves identifying critical factors influencing safety risks and imple-

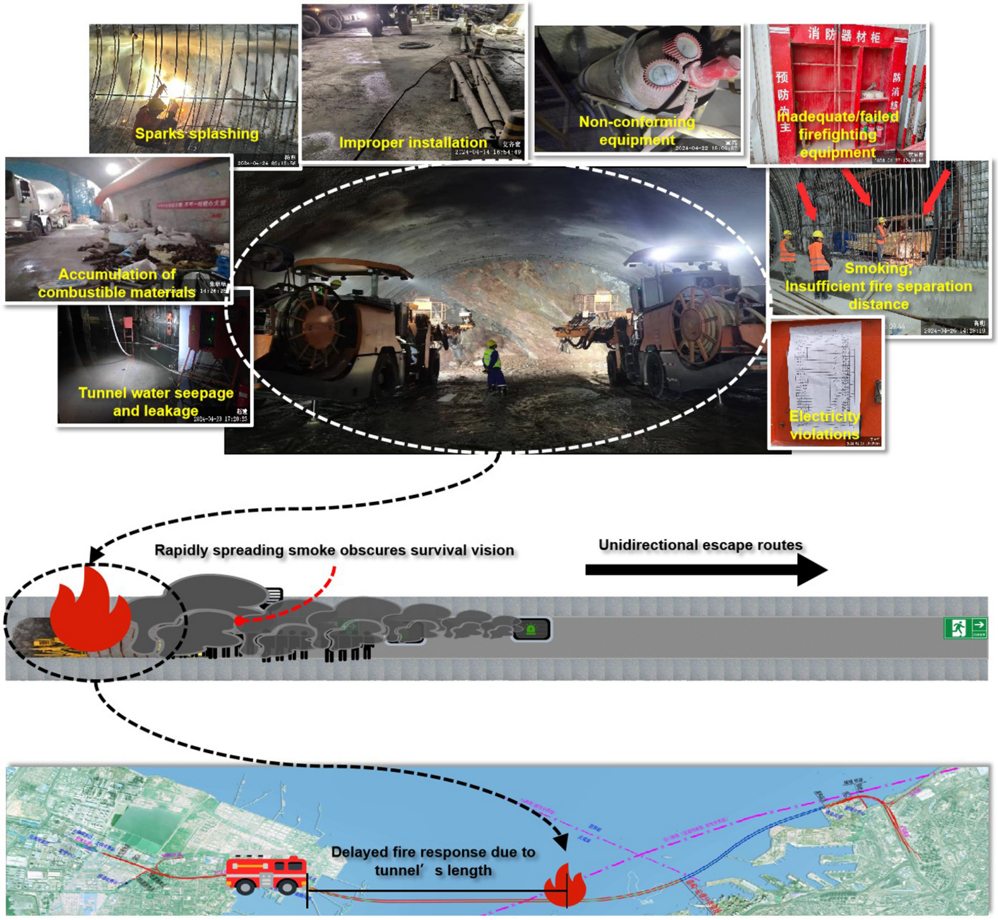

Figure 2. Characteristics of long tunnels from a fire-fighting perspective

menting targeted measures to reduce the risk level. By distinguishing the concept of long tunnels from a firefighting perspective, it is possible to propose fire risk reduction programs specifically for long tunnels. After a fire occurs in a long tunnel, the limited ventilation capacity restricts smoke dissipation due to its longitudinally elongated and internally enclosed space. Meanwhile, rapid smoke spread reduces the visual range of trapped individuals and diminishes their perception of distance. Furthermore, it increases the difficulty of evacuation and rescue (Fridolf et al., 2013; Seike et al., 2016).

The occurrence of numerous tunnel fire accidents and construction-related restrictions necessitates the implementation of fire risk assessment and safety management. Consequently, tunnel risk reduction is a crucial part of tunnel construction.

2.2. Risk reduction methods

Many scholars have researched and established construction fire risk assessment systems, with fault trees and Bayesian networks being the most common models (Wang et al., 2009; Huang et al., 2024). Fault tree analysis is a graphical representation method used to describe the causes and potential consequences of specific failure events. Logic gates (such as AND gates and OR gates) are used to show how different events combine to cause system failure (Reay & Andrews, 2002). This analysis can be quantitative or qualitative, aiming to ascertain the likelihood and impact of failure events, and is predominantly used for static assessments (Kabir, 2017; Bucci et al., 2008). Scholars have also divided the fire development process into four stages, "fire situation – fire alarm – fire risk – fire accident", and proposed the main risk assessment parameters for each stage (Shu et al., 2020).

Currently, fault tree analysis is mainly performed by on-site personnel through manual risk identification and hazard inspections, with the results submitted to risk reduction units for assessment and response. However, traditional paper-based records are prone to loss or omission, while centralized information systems depend on full trust in specific authorities, making them vulnerable to tampering and undermining transparency, fairness, and data verifiability (Wang et al., 2019; Ni et al., 2021). In addition, relying solely on a single assessment method to control risk is not reliable, as it depends heavily on specific personnel, leaving project owners unaware of on-site conditions and uncertain whether the critical factors have been addressed. Moreover, during actual construction processes, on-site conditions are continuously changing and data sources evolve, rendering fault tree analysis a dynamic and complex process. As a result, an increasing number of firms are adopting digital solutions to track the status of machinery and assign accountability to personnel. Many scholars also leverage modern information technology to assist in fire risk assessment and management on tunnel construction sites. Weng and Liao (2005) proposed and designed an expert software system and applied artificial intelligence for fire risk level assessment. Tian and Cai (2011) established a fire risk assessment software system based on the Analytic Hierarchy Process to achieve the rapid determination of fire risk levels.

As concluded above, fire risk reduction methods are crucial for tunnel construction safety risk reduction, and previous research has demonstrated that the fault tree method is a reliable risk assessment approach. However, this method also has notable drawbacks. The construction process involves various entities, and data transmission is complex, sometimes leading to data fraud. Therefore, it is necessary to implement measures to guarantee data authenticity.

2.3. Potential of integrating risk reduction method with blockchain technology

Traditional digital recording methods usually still rely on specific individuals or departments, which cannot fully eliminate the risk of data fraud. In this context, blockchain technology has emerged and gradually become an alternative method for information sharing and responsibility tracing.

Considering that tunnel construction fire risk reduction involves a large amount of information, there is a need for blockchain technology in the tunnel construction process. Blockchain technology mainly includes public chains, private chains, and consortium chains (Hyun et al., 2015). In order to ensure multiple types of information sharing among stakeholders, information should be public, and the rights and responsibilities of stakeholders should be equal. Therefore, the private chain is not suitable for tunnel construction fire risk management (Perera et al., 2020). Additionally, tunnel construction fire risk reduction involves many entities, requiring identity verification for each stakeholder to ensure the security of information. Therefore, the consortium chain is more appropriate for tunnel construction fire risk reduction (Turk & Klinc, 2017).

The WuTongChain platform was independently developed by Professor Xiaofeng Ma's research team as a consortium-chain system. It natively supports China's commercial cryptographic standards (SM2, SM3, etc.), ensuring compliance with national information-security regulations. The platform provides built-in interfaces for off-chain data path logging and on-chain hashing, and it includes an SM2-based signature-verification mechanism. This design ensures data security and reduces development and integration complexity, making it well suited to engineering scenarios that require both notarization of sensitive information and verifiable authenticity. Conducting experimental validation on a homegrown platform further enhances the reproducibility and practical feasibility of this research. Therefore, this work adopts the WuTongChain platform as the basis for the design and implementation of the proposed system. The WuTongChain platform has been applied in logistics and shipping, internet finance, and e-government (Chen et al., 2018; Du et al., 2020).

It can be concluded that fault tree analysis is a dynamic process, and blockchain can ensure data transparency during transmission. Meanwhile, project owners prefer to restrict data access to construction-related units only. Thus, it is essential not only to guarantee data authenticity but also to maintain a certain level of data privacy. Therefore, this study aims to develop a tunnel construction fire risk reduction platform based on WuTongChain.

3. Research approach

This study is guided by design thinking, which encompasses five stages: problem identification & motivation, definition of solution objectives, design, demonstration, and application (see Figure 3).

As shown in Figure 1, the initial motivation (stage 1) stems from the real-time changes in information regarding personnel, machinery, and materials at tunnel construction sites, coupled with the absence of a secure, traceable, and transparent fire risk reduction platform for tunnel construction. The literature review highlights the importance of fire risk reduction in tunnel construction, along with the data transmission required to develop an effective platform (stage 2). After reviewing the detailed literature and identifying the research gaps, the blockchain-aided fault tree method is identified as an effective approach for dynamically managing fire risk and ensuring the authenticity of information. Consequently, an information-sharing and fire-warning framework based on blockchain technology is

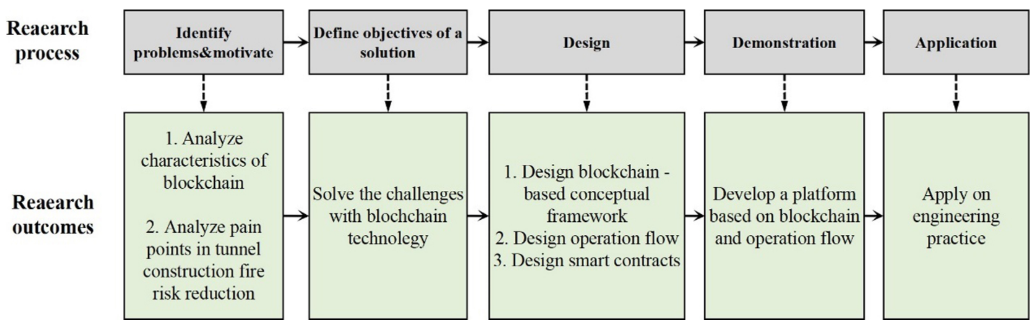

Figure 3. Research flow

proposed to store and track fire risk information, and the operational business processes of participating units are sorted out. Additionally, some smart contracts for fault tree analysis are designed to upload risk data and calculate the fire risk level (stage 3).

Based on the framework, a platform based on WuTong-Chain is developed, and a case study is conducted to demonstrate the feasibility and reliability of the platform based on on-site feedback (stages 4 and 5).

4. Blockchain-based tunnel construction fire risk reduction innovation

4.1. Fault tree analysis and information flow

The characteristics of the target being evaluated are vital in determining the performance of the assessment model and serve as an important foundation for assessing tunnel construction fire risk. Fault tree analysis is a method of hazard identification that starts with an initial event and deduces possible consequences. Based on the principles of different possible states of each event, it takes the initial event as the starting point and progressively moves through the subsequent events until it reaches an accident.

Currently, many scholars have discussed the causes of construction fires, noting that fire accidents vary in severity. The formation of general fire accidents is often closely related to the proximity between the ignition source and combustible materials; a fire could occur if the distance between the two is below a certain threshold. In contrast, significant fire accidents are more often linked to management factors. For instance, a general fire may become extensive if there is a large quantity of combustible materials and an inadequate or inappropriate number of fire extinguishers available, allowing the fire to escalate. In addition, if the on-site ventilation system is limited at this point, smoke will quickly spread, reducing visibility for construction personnel and complicating evacuation efforts, potentially leading to casualties.

After analyzing domestic and international cases of tunnel construction fires and general building fire accidents, it can be preliminarily concluded that casualties caused by fire accidents can be regarded as the top event in the fault tree. Typically, fire incidents that result in casualties progress through several distinct development stages.

(1) Fire initialization

Various ignition sources exit in tunnel construction, including violations of hot work operations, human-created ignition sources, and electrical ignition sources. Violations of hot work operations include sparks, residual welding slag/parts, and insufficient worker experience. Human-created ignition sources generally involve smoking and intentional arson. Electrical ignition sources generally include electrical sparks and wire failures, such as poor contact, overloading, improper installation of wires, mechanical damage, water leakage and external friction. Common combustible materials accumulated on construction sites include insulation foam boards, plywood, and waterproof membranes. These materials are typically highly flammable and pose significant fire hazards. When the distance between an ignition source and the piled combustible materials falls below the safety threshold, fire can spread rapidly, potentially leading to serious accidents. For example, in July 2024, a fire broke out during the construction of a building in Sichuan Province, China, after welding sparks ignited flammable insulation materials such as sandwich color steel panels. The incident resulted in 16 fatalities.

(2) Fire controls

The second stage involves the fire going out of control, typically due to insufficient firefighting capabilities. For instance, inadequate experience among on-site personnel could lead to fire spreading uncontrollably. Additionally, even if the fire is detected promptly, it may not be effectively controlled if the on-site firefighting capabilities are lacking, ineffective, or handled by inexperienced personnel. For example, in 2008, a fire occurred in a region of Xinjiang Province, China. Due to improper operation by on-duty personnel, the fire protection system was not activated in time. Additionally, the management had failed to conduct regular maintenance of the on-site fire equipment, resulting in insufficient firefighting capability and subsequent loss of control over the fire. Similarly, in 2018, a fire broke out at the Grenfell Tower apartment building in the United Kingdom. The emergency fire protection systems also failed to function effectively during the incident, which further contributed to the significant number of casualties.

(3) Fire-related casualties and losses

Finally, the failure of evacuation efforts often leads directly to casualties. On the one hand, this could be attributed the personnel themselves, such as ineffective fire drills or the emergency plan is not scientific enough, leading to inefficient decisions of survivors. On the other hand, the tunnel projects are usually linear projects, which often have long evacuation routes and high density at the working face, making unsuccessfully evacuations more likely. Furthermore, if safety evacuation signs are lost or covered, or safety exits are blocked, the chances of on-site personnel evacuation will be further reduced. For example, fires in the Mont Blanc Tunnel (1999) and the Kaprun Tunnel (2000) resulted in numerous fatalities. Due to the geometric characteristics of the tunnels and the inadequacy of their ventilation systems, many individuals died from asphyxiation and burns while attempting to evacuate.

In summary, by taking fire-induced casualties as the top event, a total of 27 basic events have been identified across the three aforementioned stages, including sparks splashing, residual welding slag/weldments, inexperienced workers, smoking, etc. A model of fault tree has been established, as shown in Figure 4 and Table 1. By using Boolean algebra to simplify the fault tree, there are a total of $12 \times 5 \times 2 \times 6 = 720$ cut sets, which means there are 720

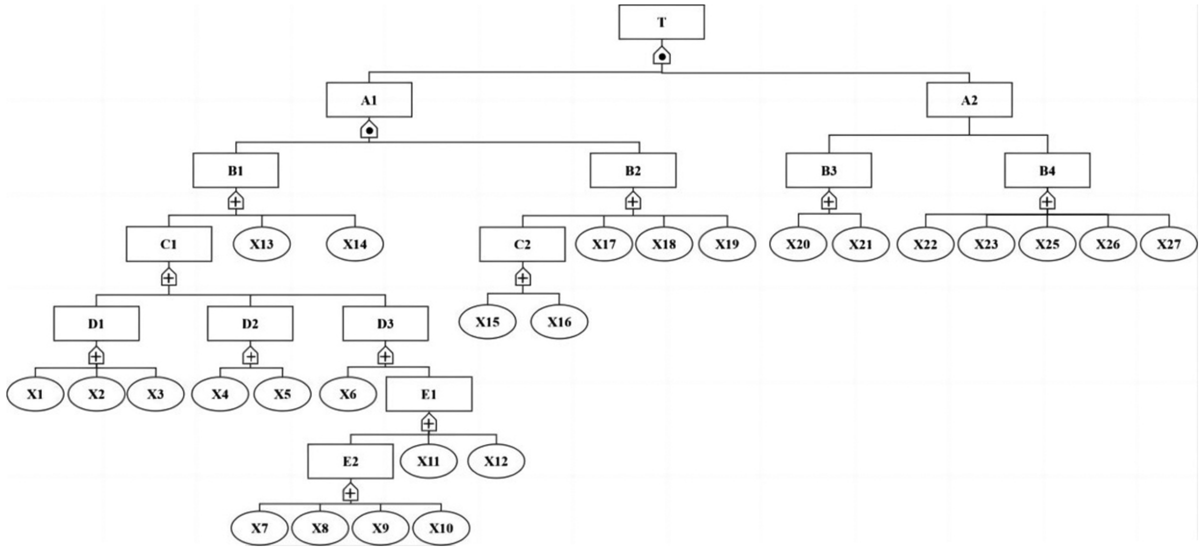

Figure 4. Fault tree analysis

Table 1. Fault and responsible unit

Number	Name	Controller	Guarantor	Number	Name	Controller	Guarantor
A1	Loss of control of the fire	CE/CS/S	–	X8	Mechanical damage	CE	CS/S
A2	Evacuation failure	CE/CS/S	–	X9	Tunnel water seepage and leakage	CS	S
B1	Fire occurrence	CE/CS/S	–	X10	External friction	CS	S
B2	Insufficient firefighting capacity	CS	S	X11	Poor contact	CS	S
B3	Inadequate personnel evacuation capability	CS	S	X12	Overload	CS	S
B4	Inadequate engineering evacuation capability	CS	S	X13	Accumulation of combustible materials	CS	S
C1	Ignition source	CE	S	X14	Insufficient fire separation distance	CS	S
C2	Delayed fire feedback	CE	S	X15	Delayed fire detection by personnel	CS	S
D1	Unauthorized hot work operation	CE	S	X16	Failure of automatic fire alarm system	CS	S
D2	Intentional open flame	CE	S	X17	Inadequate/failed firefighting equipment	CS	S
D3	Electrical ignition source	CS	S	X18	Personnel lacking fire safety training	CS	S
E1	Wire malfunction	CS	S	X19	Firefighters unfamiliar with the site	CS	S
E2	Short circuit	CS	S	X20	Inadequate fire drills	CS	S
X1	Sparks splashing	CE	CS/S	X21	Inadequate development of emergency response plans	CS	S
X2	Residual welding slag/ welding components	CE	CS/S	X22	Excessive density of personnel on-site	CS	S
X3	Inadequate worker experience	CE	CS/S	X23	Escape routes too long	CS	S
X4	Smoking	CE	CS/S	X24	Failure of emergency lighting equipment	CS	S
X5	Arson	CE	CS/S	X25	Blocked safety exits	CS	S
X6	Electrical sparks	CE	CS/S	X26	Failure of obstruction-clearing signage	CS	S
X7	Improper installation	CE	CS/S	X27	Failure of emergency broadcast system	CS	S

Notes: *CE: Construction unit – Engineering department; CS: Construction unit – Safety department; S: Supervision unit.

possible pathways leading to fire accidents at the tunnel construction site. The difficulty of prevention and control is significant.

Then the probability of the top event is calculated as follows:

$$T' = X1'X2'X3'X4'X5'X6'X7'X8'X9'X10'X11'X12' + X13' + X14' + X15'X16''X17'X18'X19' + X20'X21' + X22'X23'X24'X25'X26'X27'. \quad (1)$$

4.2. Fire risk responsibility entities

Based on the degree of impact on the fire risk level, the responsible entities can be divided into control systems and guarantee systems, as shown. The control system usually consists of the units directly responsible for the event, such as the engineering department and the safety department of the construction unit. The guarantee system generally includes the supervisors of the event status, such as the safety department of the construction unit, the supervising unit, and the fire department. Based on on-site investigations, this study identifies the controllers and guarantors for each basic event and sub-event, as detailed in Table 1.

The tunnel construction fire risk reduction platform aims to provide risk information collection services for each user at different stages and events, thereby forming a comprehensive information database that enables precise control and accurate traceability throughout the entire fire risk reduction process. The risk data collected by the platform should embody five key dimensions of information, known as 4W + 1H, meaning: time (when), location (where), personnel (who), event name (what), and collection method (how). In the management process, each participating unit is required to collect fire risk information at the construction site according to the 4W + 1H principle on a regular basis, ensuring that fire risk issues can be traced back to responsible parties. Following this principle, information for each event is collected and uploaded to the platform by the unit node. After receiving authentication from the guaranteeing unit, the information is permanently stored in a decentralized database based on blockchain technology.

4.3. Compatibility between blockchain and tunnel construction fire risk reduction method based on fault trees

Considering the shortcomings of information sharing and responsibility management in the process of tunnel construction fire risk reduction, this study highlights the advantages of blockchain technology in addressing inadequate information sharing, low interconnectivity, and unclear responsibilities, thereby achieving comprehensive fire risk reduction and responsibility tracing.

Blockchain technology stores data using a unique distributed ledger and encryption algorithms, ensuring data security and reliability, and laying the foundation for responsibility tracing. Timestamps and digital signature technology ensure data immutability, facilitating complete recordkeeping and content verification. The consensus mechanism helps address trust issues among stakeholders. Smart contracts improve response speed and enable automated audits. These characteristics enable the integration and sharing of both risk information and responsibility information, ensuring the authenticity and effectiveness of the data. Such efficient sharing is beneficial for optimizing traditional information management methods and holding parties accountable for information issues. It is evident that blockchain technology perfectly fits the requirements of information management and responsibility tracing, as shown in Figure 5.

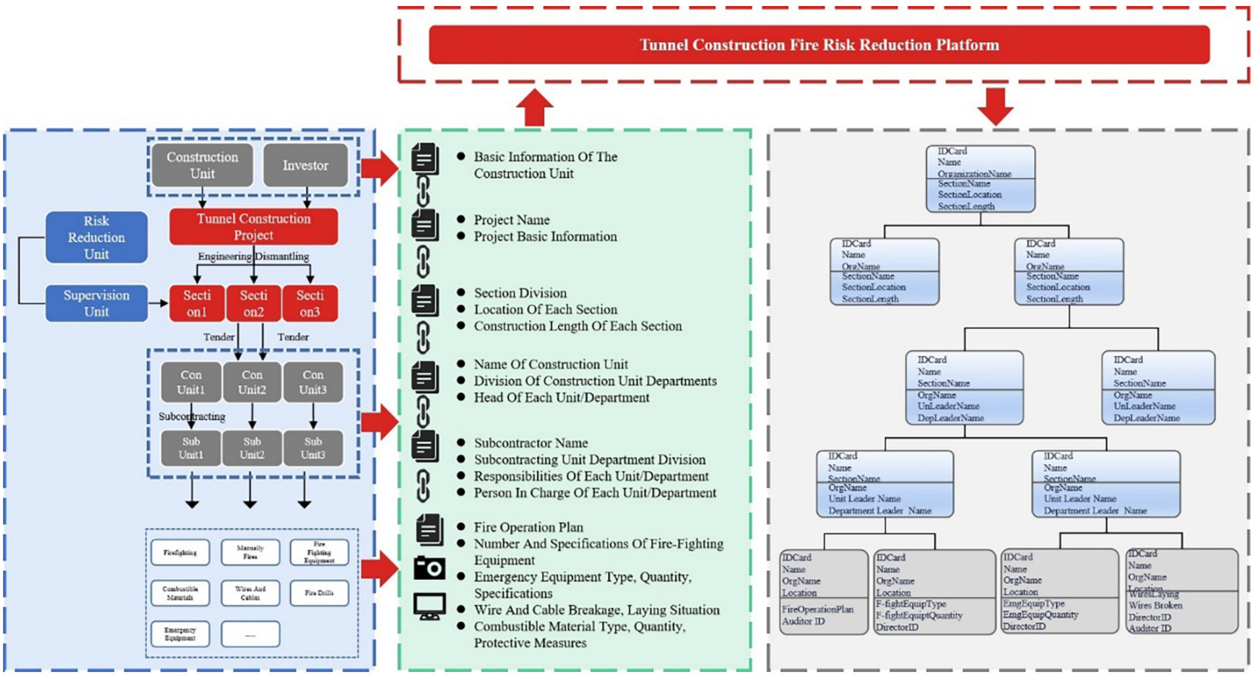

Figure 5. Information flow in the framework

5. Framework design

5.1. Data structure

Blockchain technology can benefit tunnel construction fire risk reduction by ensuring data immutability and transparency in blocks. Each block consists of two parts: (1) block header and (2) block body. The block header represents the basic information of the block, containing the index number, timestamp, Merkle root, hash values, and information about the stakeholders involved, such as the construction units and supervision units. The Merkle root links the header and the body.

Fire risk information is converted into transactions using a hashing function. After multiple hash operations, numerous transactions are consolidated into a Merkle root in the form of a binary tree. Notably, the hashing function has two main characteristics: (1) the encrypted content is difficult to deduce from the hash value; and (2) the hash value of each block will always be different, even if there is only a minor change in the input data. Moreover, blocks are chained together by two hash values: the hash of the current block and the hash of the previous block. This means that if an attacker attempts to change one hash, all the hashes in the chain between the tampered block and the latest block must also be changed. Therefore, fire risk information stored in the blocks is tamper-proof. The data structure of the blocks is shown in Figure 6.

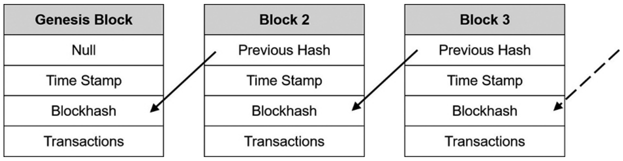

Figure 6. Basic data structure of blockchain

5.2. Smart contract

Smart contracts are typically deployed on-chain after consensus, enabling automatic responses to external messages, thereby reducing the need for manual intervention in the risk assessment process. This study aims to develop specific contracts based on the factors influencing tunnel fire risk. These smart contracts serve two main functions: (1) data uploading and (2) fire risk level calculation and alerting.

Firstly, the framework identifies the data or information uploaded manually or by machines. Once the controller and guarantor verify the content of the event, the data becomes eligible for upload to WuTongChain. Subsequently, the smart contract assigns a probability to the corresponding event according to a predefined probability table. It's noteworthy that the probability table is informed by on-site investigations and literature reviews, reflecting the varying frequencies of each basic event's occurrence. Following this, the statuses of 27 events are aggregated for risk calculation. To determine the top event probability, the smart contract is primarily structured around Eqn (1). Additionally, the smart contract outputs the calculation results along with other contextual details, such as mileage, section, time, basic event name, and status.

By deploying these two smart contracts, it becomes possible to monitor event statuses during the tunnel construction process and automatically receive alerts for potential fire risks. Figure 7 illustrates the classification standard for each node and the pseudocode for this function.

5.3. Framework process design

Responsibility management, planning management for on-site equipment and personnel are all part of fire information management. Considering all these issues, a blockchain-based fire risk information sharing platform has been designed. The platform adopts a consortium blockchain framework, which is established and maintained by organizations (construction units) participating in project management within the region. The platform primarily

Upload the events

```
Algorithm 1
Input: section, date, location, nodeContents (details about 27 events)
Output: Transaction hash
   If section, date, location, or nodeContents is missing then
      Return "Error: Missing required information"
   End If
# Define events as an empty list
   For each node in nodeContents (X1 to X27):
      Create Event with attributes:
         Name = node.Name
         Owner = node.Owner
         Controller = node.Controller
         Time = date
         Section = section
      Append Event to events list
   End For
# Define compositeKey as a identifier using section, date, location
   If putState(compositeKey, "recorded") fails then
      Return "Failed to record request"
   End If
# Upload the events to blockchain and generate a transaction hash
   Return "Transaction hash"
End
```

Calculation the fire risk

```
Algorithm 2
Input: section, date, location, nodeContents (states of various events)
Output: Risk level or warning messageTransaction hash value
If section, date, location, or nodeContents is missing then
   Return "Error: Missing required information"
End If
For each node in nodeContents:
   Name = node.Name
   ProbTable = node.ProbabilityTable
End For
# Calculate topEventProbability using formula:
   ProT = ProX1*ProX2*ProX3*ProX4*ProX5*X6*ProX7
        *ProX8*ProX9*ProX10*ProX11*ProX12
        + ProX13 + ProX14
        + ProX15*ProX16*ProX17*ProX18*ProX19
        + ProX20*ProX21
        + ProX22*ProX23*ProX24*ProX25*ProX26*ProX27
 If topEventProbability > 0.01 then
    Return "Warning: High risk, please take immediate action!"
Else
    Return "Acceptable"
End If
```

Figure 7. Smart contracts for fire risk reduction

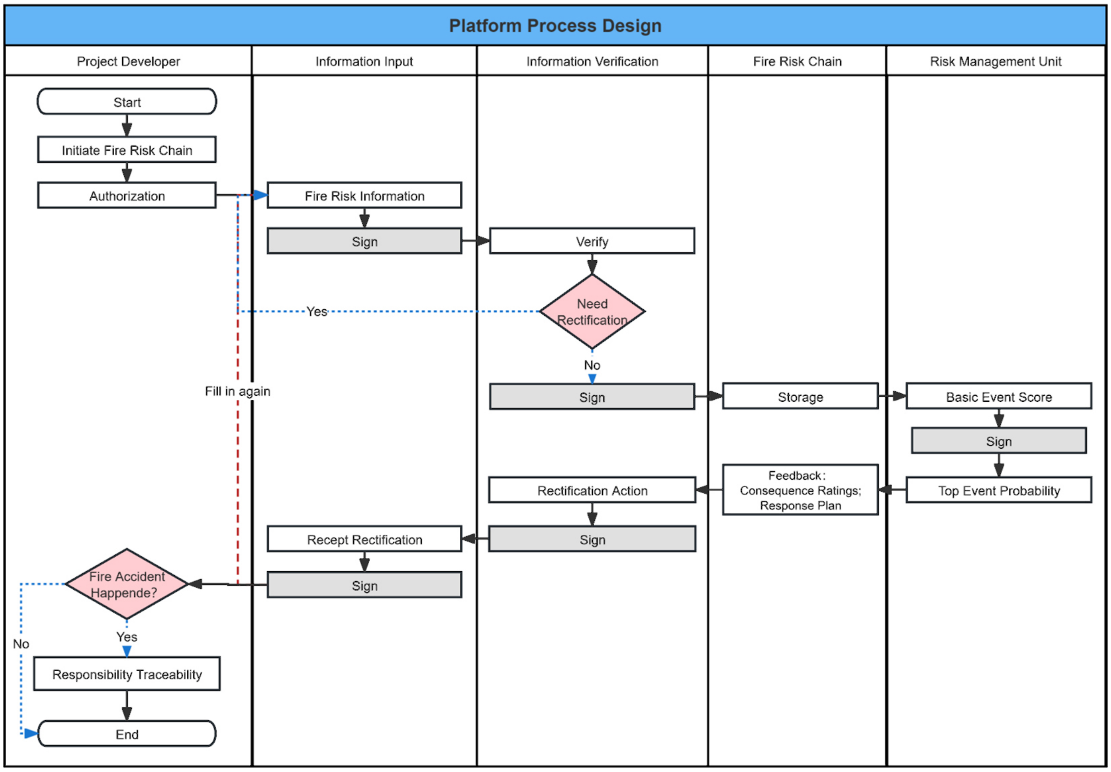

Figure 8. Operation flow

serves construction units, supervision units, and construction units, as well as third-party units such as fire departments, with IoT devices providing relevant information as a platform auxiliary. The platform process is shown in Figure 8. Users can access the platform through the application, with workflows and important information recorded on the blockchain. The platform can provide reliable information without relying on authoritative institutions. In addition, the original information database will still be used.

The platform's core functionalities are as follows, and the main process flow is illustrated below.

(1) Fire Risk Chain Information Sharing

To ensure a strong binding between on-site construction data and the individual who uploads it, the FRC platform employs an SM2-based digital signature scheme. Specifically, each user is assigned a unique cryptographic key pair generated using the SM2 algorithm, consisting of a private key and a corresponding public key. The private key remains confidential and is securely held by the user. Whenever a user initiates a data-upload transaction on the platform, they digitally sign the payload with their private key and submit the corresponding public key alongside the transaction. The verifier can then authenticate the signature by using the submitted public key and reconstructing the payload hash to verify its integrity and authenticity. This mechanism guarantees a unique, verifiable link between the uploaded information and the responsible party, thereby ensuring the integrity, authenticity, and traceability of risk-related data and clarifying subsequent attribution of responsibility.

(2) Fire Risk Chain Early Warning

Once the risk information for the same working face has been fully collected (i.e., new location risk data uploaded), the risk reduction unit reviews and scores the reported information. All events and their detailed descriptions, responsible personnel, and reporting times can be viewed on the WuTongChain. Then, the smart contract automatically computes the current fire risk probability using the predefined fault-tree calculation formula. If the computed probability exceeds the preset warning threshold, the contract issues an alert to all relevant stakeholders and pinpoints the critical nodes that most substantially influenced the elevated risk level, forwarding these details to the responsible units. The probability level of fire risk is assessed and categorized according to the national standard GB50652-2011 "Risk Management Code for Urban Rail Transit Underground Engineering Construction" (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2011) (referred to as the "national standard"). Following the national standard, the probability of risk incidents is categorized into five levels. To quantify the risk incidents for guiding risk decision-making, the invention classifies the risk levels based on different consequences of risk losses, considering four types of losses resulting from tunnel construction fire incidents: casualties among construction personnel, economic losses, schedule delays, and damage to social reputation. The highest level among these four losses is selected for determining the risk level. According to the probability of risk occurrence and the magnitude of risk losses, the engineering construction risk levels are categorized into four levels. Different risk disposal principles and control plans should be adopted for risks of varying levels. In this way, the system supports real-time, dynamic risk assessment while simultaneously ensuring clear attribution of responsibility.

5.4. The framework of the platform

This research is the first attempt to develop blockchain framework for the tunnel construction fire risk scenario. The results validated the theoretical feasibility of the proposed framework. Additionally, the risk information was recorded into blocks where the data is immutable, transparent, and traceable among fire risk reduction stakeholders. Users can trust the information record and quickly discover the reason when accidents occur via retrieving historical records.

The research has developed a tunnel construction fire risk reduction platform called Firerisk Chain (referred as FRC platform as following) based on blockchain technology. The system utilizes the Java HttpClient library to store data, such as report submissions, rectification commands, audit commands, and scoring operations in the database. The subsequent data changes can be traced using transaction IDs (shown in Figure 9). Experiments have been conducted for data entry and evaluation, and users can directly access and use the platform through a web browser.

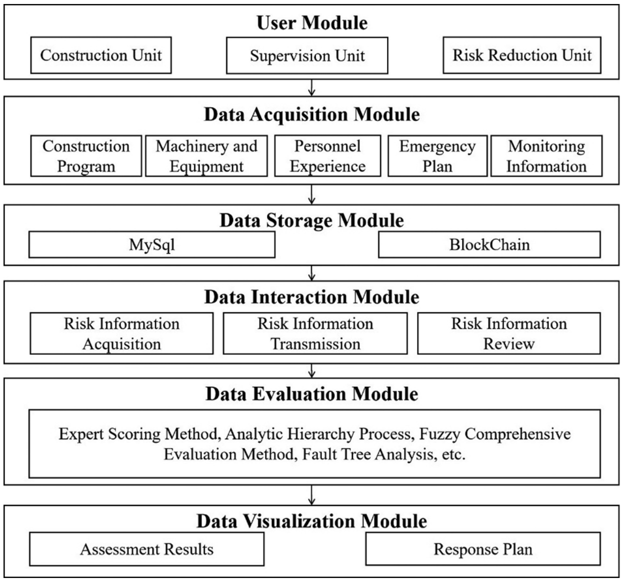

Figure 9. Characteristics of platform framework

6. Implementation and validation

6.1. Performance evaluation

To evaluate the performance of the proposed framework and ensure its timely response, two key metrics, latency and throughput, were tested under varying task loads. Low latency reflects the system's ability to respond quickly to individual requests, while high throughput demonstrates its capacity to handle tasks concurrently within a given time frame. In the framework proposed in this study, the interaction with WuTongChain primarily involves two functions: Upload and Query. The Upload function encompasses the entire process of packaging and digitally signing data, submitting it to the blockchain, waiting for on-chain confirmation, and returning the transaction hash. The Query function, in contrast, is responsible for retrieving specific transaction details based on a given hash. To evaluate their performance, we conducted stress tests on both functions, and the results are presented in Figure 10.

The Upload function exhibited significantly higher latency, consistently around 4.5 seconds, as shown in Figure 10a. This is attributable to the inherent costs of the blockchain's consensus and packaging mechanisms. However, its throughput showed a remarkably positive trend with increasing concurrency. Starting at 25.8 TPS under a load of 100 concurrent requests, the throughput grew steadily, reaching 46.5 TPS at 900 requests. Considering that the typical daily volume of data reporting on construction sites ranges between 50 and 300 entries, this level of performance fully meets the real-time requirements for emergency risk analysis. The Query function demonstrated characteristics of low latency and high initial throughput. As shown in the Figure 10b, its average latency consistently remained below 50 milliseconds under varying transaction loads. At low loads (e.g., 100 transactions), the throughput reached up to 71 transactions per second (TPS). However, a performance degradation trend was observed as

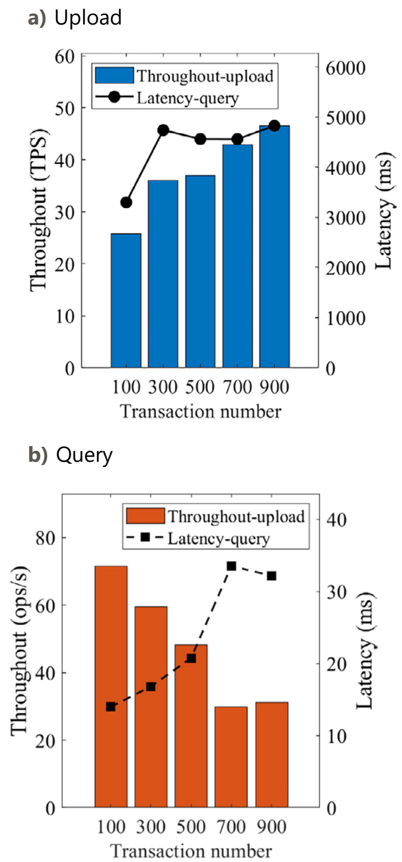

Figure 10. Stress tests

the transaction volume increased, the throughput gradually declined to 31 TPS when the number of transactions reached 900.

In conclusion, under the current system configuration, the proposed framework is well-suited to support the intended application scenarios effectively.

6.2. Cost analysis

Cost is often a primary concern for construction enterprises. When implementing a fire risk management platform, key cost components typically include computing resources, auditing fees, and associated expenditures. Compared to traditional risk management approaches, the proposed framework offers two significant advantages:

(1) As a consortium blockchain, the platform operates without gas fees, thereby substantially lowering ongoing expenses. Moreover, unlike other consortium blockchains that may encounter adoption barriers in China due to a lack of official oversight and resulting trust issues, this framework is designed to comply with regulatory standards, enhancing its credibility and suitability for localized implementation.

(2) The platform ensures data integrity through transparent and tamper-proof transmission mechanisms, facilitating effective accountability and responsibility tracing in the event of a fire incident. In contrast, traditional methods often face challenges such as data inaccuracy or loss, which hinder timely on-site corrections and obscure the determination of liability.

Overall, the proposed blockchain-based framework represents a cost-effective and trustworthy alternative to conventional platforms, especially in contexts where high standards of transparency, traceability, and regulatory compliance are required.

7. Case study

This platform is utilized for the construction project of the Jiaozhou Bay Second Submarine Tunnel in Qingdao, hereinafter referred to as the "Second Tunnel project". The construction site of the Second Tunnel project is characterized by strong spatial confinement, multiple potential combustibles, and challenges in firefighting, where fire incident could lead to severe consequences. The daily safety inspection checklist for the Second Tunnel project has repeatedly highlighted issues such as insufficient or ineffective fire extinguishers, arbitrary laying of electrical wires and cables, and improper storage of hazardous materials. These persistent issues are attributed to a lack of safety awareness among on-site personnel and unclear responsibilities of supervisors. Therefore, the implementation of fire risk reduction through the FRC platform is considered necessary. In routine construction operations, once roles have been assigned to the responsible parties on the FRC platform, the workflow consists of three main steps-data collection, automated risk assessment, and on-chain recording of information, as illustrated in Figure 11. An analysis of the frequency of various events is summarized in Table 2.

The fire risk probability level for the Second Tunnel project is assessed and categorized according to the national standard GB50652-2011 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2011). The levels are determined based on risk probability, losses, and acceptance criteria, as shown in Tables 3, 4 and 5.

For instance, in the second week of March 2023, construction of the secondary lining was taking place at the site. The specific construction process involved: laying geotextile fabric, placing waterproof boards, installing rebar for

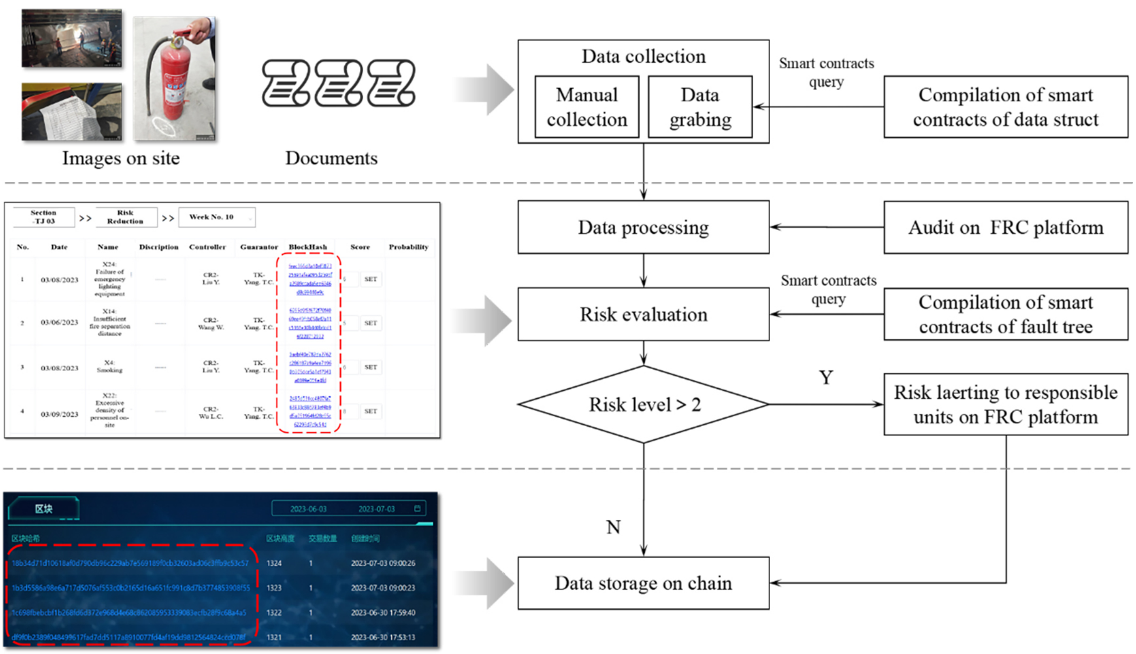

Figure 11. Risk information flow in the platform

lining, positioning the trolley, installing end framework and water stoppers, pouring concrete, dismantling the framework, and curing the concrete.

Potential sources of fire present during this process included: improperly laid electrical wires, potential mechanical damage (with the possibility of the trolley running over wires), sparks from welding work, and falling weldments. Combustible materials present included waterproof boards, geotextile fabric, foam rubber, and wooden boards. The current on-site firefighting capabilities, including fire extinguishers, self-rescue breathing apparatus, and other equipment, are deemed sufficient for the construction scenario. The relevant information is reported by various departments, reviewed by the control unit, and then synchronized to the risk reduction unit.

A risk assessment is conducted by risk reduction experts, and the FRC platform calculates the probability of a fire incident resulting in casualties is also 0.28, with a probability level of 1. Due to the large number of construction personnel on site and the abundance of combustible materials, there is a possibility that a fire could become uncontrollable. Consequently, experts have assessed the potential consequences of an accident as Category C. According to standards, the risk level for this situation should be classified as *Level* I, indicating a relatively high level of risk. Events X7, X13, X14, and X15 receive lower scores, and the response measures are recommend as following: (1) Construction unit-engineering department to adjust the location of combustible storage, to maintain a suitable fire distance; (2) Construction units-engineering department and safety department to strengthen the fire safety awareness of construction personnel education; (3) Supervision unit to strengthen the inspection, tracking the implementation of the construction unit. The detailed description and responsible parties for each event can be traced using blockchain hash values on the WuTongChain, ensuring transparency and accountability.

In practical application, once a fire incident occurs, the platform activates its responsibility-tracing mechanism. The SM2-based digital signature scheme implemented in the FRC platform ensures that all uploaded information is cryptographically signed by the responsible units. During the tracing process, if the authenticity of the original data needs to be verified, the platform can retrieve the recorded

Table 2. Probability of basic events occurrence

Event No.	Base Probability	Event No.	Base Probability	Event No.	Base Probability
X1	0.02277	X10	0.00641	X19	0.00243
X2	0.02277	X11	0.04332	X20	0.00508
X3	0.00508	X12	0.04332	X21	0.00243
X4	0.00508	X13	0.00398	X22	0.00133
X5	0.00508	X14	0.00398	X23	0.00088
X6	0.02277	X15	0.00508	X24	0.00199
X7	0.04332	X16	0.00243	X25	0.00088
X8	0.04332	X17	0.02962	X26	0.00707
X9	0.00243	X18	0.00508	X27	0.00243

Table 3. Risk probability level standards

Level	1	2	3	4	5
Description	Frequent	Likely	Occasional	Rare	Improbable
Interval Probability	> 0.1	0.01~0.1	0.001~0.01	0.0001~0.001	< 0.0001

Table 4. Risk losses level standards

Level	A	B	C	D	E
Severity of the Situation	Catastrophic	Very serious	Serious	Needs consideration	Negligible

Table 5. Risk losses level standards

Interval Probability		A	B	C	D	E
		Catastrophic	Very serious	Serious	Needs consideration	Negligible
1	Frequent	Level I	Level I	Level I	Level II	Level III
2	Likely	Level I	Level I	Level II	Level III	Level III
3	Occasional	Level I	Level II	Level III	Level III	Level IV
4	Rare	Level II	Level III	Level III	Level IV	Level IV
5	Improbable	Level III	Level IV	Level IV	Level IV	Level V

signature and the corresponding public key submitted by the uploader, and verify them using the SM2 verification process. If the verification succeeds, it confirms that the data were indeed signed by the original user and have not been tampered with, thereby providing a trustworthy basis for determining liability, as shown in Figure 12. By applying this platform, the construction unit could decrease the probability of fire risk, thereby save lives of construction on-site and costs caused by fire accident.

8. Discussion

In the process of undersea tunnel construction management, fire-risk inspections usually rely on on-site patrols by construction personnel. However, the construction site involves multiple stakeholders and multi-source data, leading to repeated on-site hazards and unclear responsibilities after an accident, which greatly increases fire risk. Therefore, it is urgent to establish an effective fire-risk management system for undersea tunnel construction by means of emerging scientific and technological methods.

In order to achieve this goal, the present study proposes a blockchain-based Tunnel Construction Fire Risk Control platform (FRC). In response to the characteristics of multiple stakeholders and multi-source risk data on the construction site, the platform innovatively introduces a fault-tree risk-analysis method based on blockchain technology, employs smart contracts for transparent sharing and automatic early warning of fire-risk information, and combines digital-signature technology to design an incident-responsibility-tracing management system. The platform has the following innovative characteristics:

1. The FRC platform adopts the WuTongChain framework, which provides distributed storage functionality to ensure data synchronization and disaster recovery across multiple nodes; it natively supports national commercial cryptographic algorithms such as SM2 and SM3, meeting China's information-security compliance requirements.
2. By introducing a digital-signature technology, the platform clarifies the identity credibility of each responsible party during data upload and confirmation, achieves multi-role data sharing and a non-repudiable responsibility-tracing mechanism, and provides data-sharing and verification support for all parties.
3. After integrating dispersed fire-hazard information from the construction site into a fault tree with 27 basic events, the platform implements the top-event probability calculation in Go language, realizing automated fault-tree risk analysis. Risk information obtained by the owner through routine inspections is automatically written on-chain and converted into risk levels, enabling risk prevention and control without relying on expert assessment and thereby reducing additional management costs.

Compared with traditional centralized platforms, this platform offers higher reliability and efficiency in data tracing while significantly reducing the costs of fire-risk warning and prevention.

However, this study still has the following limitations:

1. Owners typically deploy multiple monitoring devices to eliminate fire hazards. Although video and image data facilitate efficient fire-risk analysis, it is challenging for blockchain to store such large-volume data. Therefore, it is necessary to conduct in-depth research on how to extract key information and record it on the blockchain.
2. At present, the platform has only been tested and validated in a laboratory environment. If existing operational data are migrated to the new system, owners will face high-cost investments. Therefore, a cost-benefit analysis must be carried out in future applications.

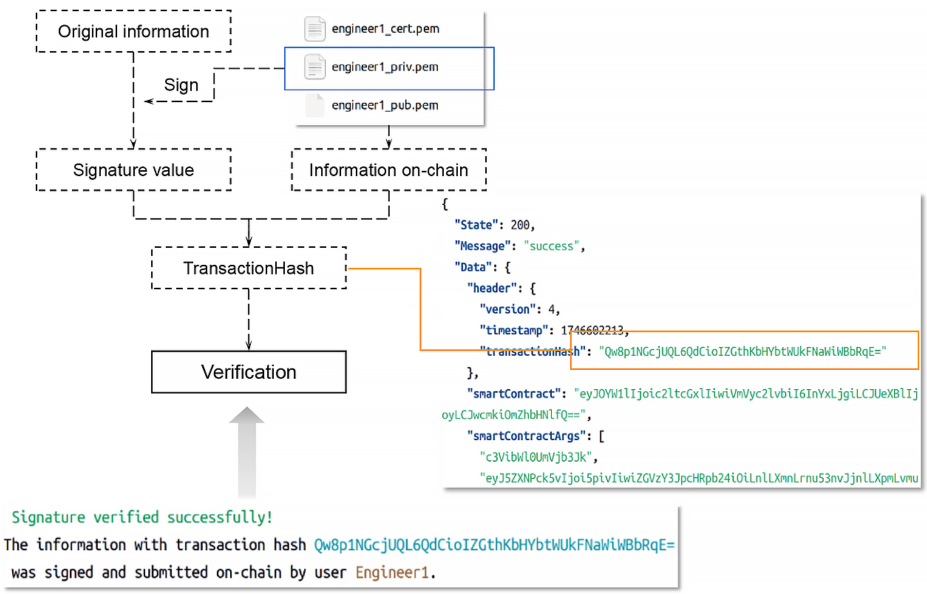

Figure 12. Traceability verification

9. Conclusions

Fire risk reduction at tunnel construction sites is typically managed through self-inspections conducted by construction and supervision units. This process involves issuing corrective lists or reporting to a digital management system to identify daily fire hazards, thereby reducing the probability of fire incidents. However, despite these measures, fire accidents still occur frequently. The root causes often include failure to adhere to construction regulations, delays in rectifying on-site hazards, or negligence by supervision units in reporting hazards promptly.

To address the challenges, this study proposes an integrated fire risk reduction approach that combines fault tree analysis with blockchain technology. A blockchain-based framework is developed to enable secure sharing of fire risk information and traceability of responsibilities. This framework not only supports dynamic risk level assessment but also facilitates the identification of responsible units involved in incident resolution, thereby enhancing post-incident accountability. Smart contracts are employed to automate the entire process, minimizing the risk of external manipulation. The incorporation of fault tree analysis ensures a comprehensive identification of potential fire risk factors, while a dual-responsibility mechanism guarantees that all fire-related information is accurately delivered to the appropriate parties. Meanwhile, blockchain ensures transparent, tamper-resistant dissemination of risk information and digital signature technology enables verifiable responsibility tracing. To validate the proposed approach, a prototype system named FireriskChain was implemented. Experimental results demonstrate that FireriskChain provides reliable fire risk data to construction, supervision, and risk mitigation entities, and effectively supports fire vulnerability tracking in real-time construction scenarios through the use of digital signature technology, offering a robust and traceable solution for fire risk reduction.

In the future, there are still areas for exploration within the fire risk reduction framework . Future research could focus on the integration of blockchain technology with real-time monitoring of equipment status and automatic identification of unsafe behaviors. This integration would enable dynamic and real-time predictions of the fire risk occurrences probabilities, further enhancing fire risk reduction at tunnel construction sites.

Acknowledgements

This research was supported by the Qingdao Guoxin Jiaozhou Bay Second Submarine Tunnel Co., Ltd (No. kh0023020222333).

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